The smart-cartridge hierarchy and μ-band adaptive control disclosed herein are equally applicable to non-therapeutic continuous-flow processes. Unless explicitly limited, every claim, description and figure of the present specification shall be construed *mutatis mutandis* to a process fluid in place of a human subject; sensor variables such as pH, red-ox potential, chlorine residual or dissolved oxygen may be substituted for biochemical analytes, and therapeutic dose ceilings may be replaced by batch-mass or throughput ceilings. Accordingly, the core intellectual property spans both medical and industrial embodiments without narrowing the scope of the appended claims.

Four-part claim clauses (verbatim)

1. **Context-limitation (therapeutic)**
   "…wherein the measured variables comprise at least one blood or interstitial biochemical analyte in a human patient."
2. **Safety + learning combination**
   "…and wherein the controller includes a learning module that updates a patient-specific Jacobian while an override layer enforces inter-analyte guard-rails."
3. **Digital-descriptor cartridge element**
   "…where each therapeutic cartridge stores a digital descriptor, and the controller disables actuation upon detecting a class conflict with an active cartridge."
4. **Conflict-graph hierarchy**
   "…a multi-tier signal-selector in which a higher-priority vital-override signal suppresses lower-priority optimiser signals according to a pre-defined incompatibility graph."

(Add these as dependent claims or incorporate them directly into an independent claim—either way they preserve the "amazing" hierarchy + cartridge novelty for both industrial and patient uses.)

Cartridge-identifier / conflict-rules clause

"…wherein the cartridge identifier is dynamically re-evaluated against a set of physiologic-state rules and inter-cartridge conflict rules, and actuation of a second cartridge is suppressed when the conflict rules predict a harmful drug–drug or drug–state interaction."

Dose-ceiling projection clause

*"…the cartridge identifier further encodes a cumulative **mg kg⁻¹** ceiling and a chemical-class tag; the controller tracks patient weight and disables the cartridge when a forward-looking 30-minute dose projection would exceed the ceiling."*

μ-band–scaled probe-amplitude clause

"…wherein the probe-pulse amplitude is automatically scaled according to the stored μ-band width such that $\Delta U \leq 0.05 \times (\mu\text{-HIGH} - \mu\text{-LOW})$, and is reduced by at least 50 % once the 95 % confidence interval of the corresponding Jacobian row falls below one-half the population standard deviation."

Independent industrial (process-fluid) apparatus claim

A chemical-delivery skid comprising:

(a) at least three replaceable reagent cartridges, each comprising an EEPROM storing (i) a chemical-class code, (ii) a batch-mass limit, and (iii) ratio limits versus at least one other class;

(b) a sensor array producing at least one process variable selected from the group consisting of pH, red-ox potential, chlorine residual, dissolved oxygen, conductivity and turbidity;

(c) a controller executing a three-layer arbitration algorithm that

- (L-0) disables flow when any process variable exceeds an emergency threshold stored in the EEPROM,
- (L-1) scales or suppresses cartridge flow to maintain the stored ratio limits, and
- (L-2) adjusts cartridge flow according to an optimisation objective,

wherein the controller updates a process-specific Jacobian matrix during sub-threshold micro-dosing periods and thereafter applies the updated matrix in layers L-1 and L-2.

Optional dependent claim—adaptive selector hierarchy

"…wherein the three-layer arbitration algorithm further includes a signal-selector that receives at least two candidate actuation values for a shared valve or pump and passes only the value generated by the highest-priority layer whose safety constraints are satisfied."

CLAIMS

1. A closed-loop therapeutic system comprising:

(a) a sensor array that simultaneously measures at least twenty biochemically distinct analytes in a human patient;

(b) a therapeutic actuator assembly including at least five independently addressable reagent cartridges; and

(c) a hierarchical arbiter that (i) ranks sensor deviations by harm-severity and time-to-harm, (ii) enforces predefined inter-analyte ratio constraints, and (iii) suppresses or delays any cartridge actuation whose EEPROM-encoded drug-class code conflicts with a drug-class code of a cartridge that is already energised.

CLAIMS:

1. **A closed-loop micronutrient–therapy system** comprising:
   a. a wearable multi-analyte sensor array that simultaneously measures at least five ions selected from Na^{+}, K^{+}, Cl^{-}, Ca^{2+}, Mg^{2+}, Zn^{2+} and Cu^{2+} in a patient-derived biofluid;
   b. a plurality of replaceable infusion cartridges, each cartridge storing a digital descriptor that encodes (i) drug-class code, (ii) cumulative mg kg^{-1} ceiling and (iii) inter-cartridge conflict tags;
   c. miniature pumps coupled to the cartridges and capable of delivering micro-boluses of ≤50 µL with ±5 % accuracy;
   d. a hierarchical controller having at least three arbitration layers in which an upper-priority vital-override layer can suppress or cancel a lower-priority optimiser layer according to a pre-defined incompatibility graph; and
   e. safety logic that disables energisation of any cartridge whose descriptor conflicts with an active cartridge or whose projected 30-minute dose would exceed its encoded mg kg^{-1} ceiling.
2. The system of claim 1, wherein the sensor array is a sweat-patch that employs iontophoresis to induce perspiration and includes on-patch calibration pulses of Cu^{2+}/Zn^{2+} to maintain electrode accuracy.
3. The system of claim 1, wherein the controller computes a patient-specific Jacobian matrix during periods in which each analyte resides inside a micro-threshold µ-band and thereafter updates guard-rail constraints with the learned coefficients.
4. The system of claim 1, wherein cartridge EEPROM data are re-evaluated on every control cycle against current physiologic state rules, and actuation of a second cartridge is suppressed when conflict rules predict a harmful drug–drug or drug–state interaction.
5. The system of claim 1, wherein every pump stroke, sensor sample and arbitration decision is time-stamped, cryptographically signed and appended to an immutable audit ledger.
6. The system of claim 1, further comprising a fallback logic layer that substitutes a model-based virtual sensor value when any physical sensor drops out for longer than a configurable T_fail interval.
7. The system of claim 1, wherein the hierarchical controller resides on a bedside micro-controller that executes latency-critical PID calculations locally while delegating fleet-wide model retraining to a cloud service.
8. The system of claim 1, wherein integral wind-up in each PID loop is prevented by clipping the controller output inside safety envelopes supplied by the safety-check layer.
9. The system of claim 1, wherein guard-rail algebra enforces inter-mineral ratios selected from Zn : Cu, Ca : Mg, Na : K and Ca × P.
10. The system of claim 1, wherein an antidote cartridge containing a chelating agent is automatically energised when a heavy-metal sensor exceeds a preset threshold and simultaneous mineral-replacement cartridges are paused until the concentration returns to target.
11. The system of claim 1, further comprising a clinician override interface that allows a role-based, time-bounded override of any loop, the override automatically expiring and re-arming the loop after a pre-set interval.
12. The system of claim 1, wherein each infusion cartridge contains an in-line flow sensor and an actuator-feedback verifier raises a drift fault when commanded and measured flow differ by more than 5 % for at least three seconds.
13. The system of claim 1, wherein battery state of charge below 10 % forces the controller into a monitor-only mode that maintains sensing and logging while disabling all pumps.
14. The system of claim 1, wherein the controller pushes anonymised telemetry to a cloud service over TLS 1.3 and pulls signed firmware or parameter updates only after verifying the update digest against the audit ledger.

15. The system of claim 1, wherein the total adhesive skin-contact area of the sensor arrays is less than 60 cm^2 while supporting at least 20 concurrent biochemical channels.

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16. **A disposable micro-dose infusion cartridge** for the system of claim 1, comprising:
    a. four isolated additive reservoirs respectively containing copper, combined calcium-magnesium, multi-trace-element cocktail and a user-selectable macro-additive;
    b. a dedicated micro-pump for each reservoir, each pump including an integral one-way check valve;
    c. a low-dead-volume mixing manifold in which the four streams converge; and
    d. a cartridge identifier memory that stores concentration, daily ceiling and chemical-class code for each reservoir.
17. The cartridge of claim 16, wherein each reservoir is held under a slight positive pressure of 50–100 mbar to suppress cavitation.
18. The cartridge of claim 16, wherein the mixing manifold volume is no greater than 20 µL to minimise pocket-effect concentration spikes.
19. The cartridge of claim 16, wherein the identifier memory locks the pumps if the cartridge is inserted after its expiry date.
20. The cartridge of claim 16, wherein flow verification is achieved by an on-pump thermal-mass or Coriolis sensor with ±5 % accuracy.
21. The cartridge of claim 16, further comprising a luer-lock outlet configured to connect downstream of an air-in-line detector.
22. The cartridge of claim 16, wherein the entire wet path is composed of medical-grade PEEK and PTFE to ensure chemical compatibility with concentrated trace solutions.

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23. **An enteral side-stream micronutrient-balancing apparatus** comprising:
    a. a Y-connector that diverts less than 2 % of bulk enteral nutrition flow into a side-stream;
    b. a peristaltic micro-pump that circulates the side-stream through a sensor module and returns it to the main line pressure-neutrally;
    c. a sensor module that provides real-time measurements of at least Cu^{2+} and the Ca : Mg ratio; and
    d. a trace-solution infusion pump that injects an ultra-concentrated additive downstream of the sensor module in response to control commands from the controller of claim 1.
24. The apparatus of claim 23, wherein the sensor module has an internal dead volume not exceeding 2 mL to improve response time.
25. The apparatus of claim 23, wherein the trace-solution pump delivers additive pulses no larger than 5 µL so that total volumetric load on the feeding tube is negligible.
26. The apparatus of claim 23, wherein all wetted components are DEHP-free and ISO 80369-compliant.
27. The apparatus of claim 23, wherein sensor readings are streamed over BLE 5.0 to the controller and cryptographically logged.
28. The apparatus of claim 23, wherein the micro-pump halts automatically if side-stream pressure exceeds a preset safety threshold.
29. The apparatus of claim 23, wherein the apparatus is configured to run unattended for at least 24 h in a home-enteral-nutrition setting.

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30. **An iontophoresis-enabled sweat-sensing patch** comprising:
    a. an active electrode including a hydrogel reservoir loaded with Cu^{2+} and Zn^{2+} ions;
    b. a return electrode spaced apart from the active electrode;
    c. a constant-current driver limited to 0.25 mA that drives ions through skin to induce sweat; and
    d. a stacked sweat sensor array positioned beneath a porous barrier and electrically isolated from the iontophoresis current.
31. The patch of claim 30, wherein current density does not exceed 0.05 mA cm^{-2}.
32. The patch of claim 30, wherein the hydrogel pH is buffered to 5.5 ± 0.2.
33. The patch of claim 30, wherein a reverse-polarity pulse is applied after each measurement cycle to clear residual ions.
34. The patch of claim 30, wherein sensor electrodes include gold interdigitated arrays coated with ion-selective membranes for Cu^{2+} and Zn^{2+}.
35. The patch of claim 30, wherein data latency from pulse initiation to sensor readout is less than five minutes.
36. The patch of claim 30, wherein patch data are compressed and transmitted to the controller via BLE-5 at intervals of no more than one minute.
37. The patch of claim 30, wherein the patch is single-use and designed for a wear period of up to 72 h.

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38. **A diagnostic-only sweat-sensor system** comprising:
    a. a passive adhesive patch bearing at least three ion-selective electrodes;
    b. a flexible tether that routes analogue signals to an external reader; and
    c. a handheld reader that provides sensor excitation, digitises signals, displays analyte concentrations and stores records in non-volatile memory.
39. The system of claim 38, wherein the patch contains no on-board battery or RF transmitter.
40. The system of claim 38, wherein the reader uploads logged data to a mobile device via NFC or BLE upon user command.
41. The system of claim 38, wherein the reader includes galvanic isolation between the sensor front-end and any charging port.
42. The system of claim 38, wherein the reader performs auto-zero calibration using a precision resistor ladder before first use.
43. The system of claim 38, wherein the patch EEPROM records a first-peel timestamp to prevent re-use beyond 12 h.
44. The system of claim 38, further comprising firmware that refuses to accept unsigned updates, thereby preserving diagnostic integrity.

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45. **A computer-implemented method** for autonomously titrating micronutrient infusions, comprising the steps of:
    i. receiving a vector of measured analyte concentrations from the sensor array of claim 1;
    ii. translating deviations from target into physical pump-stroke commands via a mapping engine;
    iii. clipping each command within safety envelopes;
    iv. vetting clipped commands against inter-analyte guard-rails and cartridge conflict rules;
    v. issuing pump commands only when no conflict is detected; and
    vi. logging all sensor inputs and issued commands in an immutable ledger for audit purposes.

46. The method of claim 45, further comprising periodically substituting virtual-sensor estimates for any channel whose live signal drops out, and continuing steps ii–vi using the virtual values until the live signal resumes.
47. The method of claim 45, wherein guard-rail algebra is solved as a quadratic-constraint optimisation that simultaneously enforces at least two mineral-ratio limits.
48. The method of claim 45, wherein the mapping engine parameters are updated by recursive least squares using data collected when each analyte is within its µ-band.
49. The method of claim 45, wherein the issued pump commands are automatically suspended when a watchdog sentinel detects actuator drift exceeding 5 % for longer than three seconds.
50. The method of claim 45, wherein a clinician override temporarily bypasses step iv for a bounded interval not exceeding a role-based maximum of 30 minutes, after which the guard-rails are automatically re-armed and step iv resumes.